Cross-Sector Impact Analysis of Industrial Process and Materials Improvements

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ABSTRACT

The industrial or manufacturing sector is a foundational component to all economic activity. In addition to being a large direct consumer of energy, the manufacturing sector also produces materials, products, and technologies that influence the energy use of other economic sectors. For example, the manufacturing of a lighter-weight vehicle component affects the energy required to ship that component as well as the fuel efficiency of the assembled vehicle. Many energy efficiency opportunities exist to improve manufacturing energy consumption, however comparisons of manufacturing sector energy efficiency investment opportunities tend to exclude impacts that occur once the product leaves the factory. Expanding the scope of analysis to include energy impacts across different stages of product life-cycle can highlight less obvious opportunities and inform actions that create the greatest economy-wide benefits. We present a methodology and associated analysis tool (LIGHTEnUP – Lifecycle Industry GHgas, Technology and Energy through the Use Phase) that aims to capture both the manufacturing sector energy consumption and product life-cycle energy consumption implications of manufacturing innovation measures. The tool architecture incorporates U.S. national energy use data associated with manufacturing, building operations, and transportation. Inputs for technology assessment, both direct energy saving to the manufacturing sector, and indirect energy impacts to additional sectors are estimated through extensive literature review and engineering methods. The result is a transparent and uniform system of comparing manufacturing and use-phase impacts of technologies.

Introduction

The United States (U.S.) manufacturing sector has seen a strong upward trend in energy productivity in the past decade resulting in greater GDP per energy input (EIA 2013). While some of this improvement is attributable to sustained industrial innovation and energy efficiency investments (IEA 2012), this is also the result of a combination of a shift from a manufacturing to a service-based economy (De la Rue du Can, 2010), and a weakening manufactured goods trade balance (USDOC 2013). This trend has continued despite volatility in the costs of energy, including all-time highs in petroleum costs and, more recently, low natural gas costs. Resilience in the face of uncertain energy costs can be improved through energy efficiency, continuous innovation, and the development of next-generation technologies and processes, which will also improve U.S. manufacturing competitiveness. A strong domestic manufacturing sector is important for the U.S. to make advancements in manufacturing innovation, leads to a strong economic multiplier effect, and creates manufacturing jobs. Recent "insourcing" decisions that increase domestic manufacturing capacity (Fishman 2012) as well as increased U.S. oil and natural gas production forecasts (IEA 2012) provide optimism for U.S. manufacturing sector growth. However, in addition to manufacturing sector opportunities, there are opportunities for the entire U.S. economy to reduce energy consumption in the use-phases of manufactured products that deliver comparable service yet consume less energy.

There is a need to evaluate opportunities to accelerate greater overall social efficiencies that are currently obscured by short-term market perspectives. These opportunities exist, but require a long-term view of manufacturing opportunities. Traditional industry energy analysis tends to evaluate technologies narrowly, where impacts are assessed at the plant level or perhaps on an industry sub-sector basis (USDOE 1999-2007; NAS 2010). While useful for understanding the magnitude of changes required within a facility or the manufacturing sector, this approach is limited with respect to technology, material, process, emission, cost, and opportunity characterization. What is required is a framework that captures not only energy intensity, but also carbon intensity (energy and process) and use intensity (i.e., provides the same end-use service but with a different material or product) within a lifecycle context. Past work on technology characterization has included exergy-based assessments (Reistad 1992); this work is focused on direct and indirect energy use. Our goal is to develop a flexible but data-driven lifecycle analysis architecture that enables a more comprehensive calculation of energy and associated impacts.

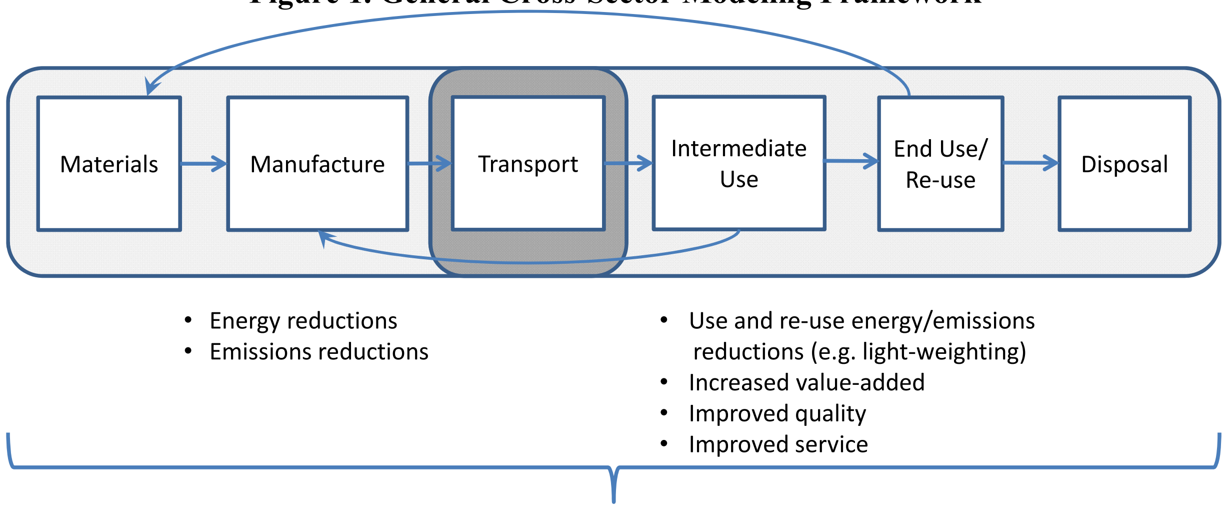
Our objective is to provide policy makers with insights for manufacturing sector measures that can have high-impact in reducing energy consumption and emissions across a broad range of the U.S. economy. We are developing a transparent and easily accessible framework to evaluate manufacturing sector investments and energy demand impacts across major energy consumption sectors of the U.S. economy and over multi-year projection periods. This is significantly more complex than traditional industrial energy use analysis because the inter-relationships between manufacturing sectors are complex (see Figure 1). Moreover, the inter-relationships between manufacturing sector outputs and consumer choices and technology adoptions amplify the complexity. The transparency of an analysis framework can easily be lost by details that do not significantly alter conclusions. Thus, our effort is to create an intuitive framework for evaluating impacts that is straightforward to utilize yet provides defensible results. The framework requires minimal inputs, but requires careful and dedicated attention and documentation of these few inputs. This provides analysts with an opportunity to clearly document assessment assumptions as well as allowing future analysis to leverage results in additional impact assessments, estimates, and scenarios.

This manuscript presents an overview of the framework as well as two select examples of measures and results. The examples are carefully selected to provide a review of how this framework can be utilized. Furthermore, these examples offer an opportunity for analysts to discuss and refine techniques for measuring and understanding the opportunities for increasing U.S. energy efficiency across the multiple sectors of the U.S. economy. It concludes with a discussion of challenges and next-steps for further developing this analysis tool.

Methodology

One of the objectives of the tool is to be able to assess the lifecycle energy impacts of implementing a particular technology measure. Figure 1 illustrates a lifecycle (cradle to grave) approach utilized by DOE's Advanced Manufacturing Office. However, this iteration of the tool (named LIGHTEnUP (Lifecycle Industry GHgas, Technology and Energy through the Use Phase)) development, as well as this paper, focuses on the manufacturing, transport, and use phases by modeling manufacturing measures and sub-measures that are independently assessing different energy impacts from manufacturing to use-phase.

Figure 1. General Cross-Sector Modeling Framework



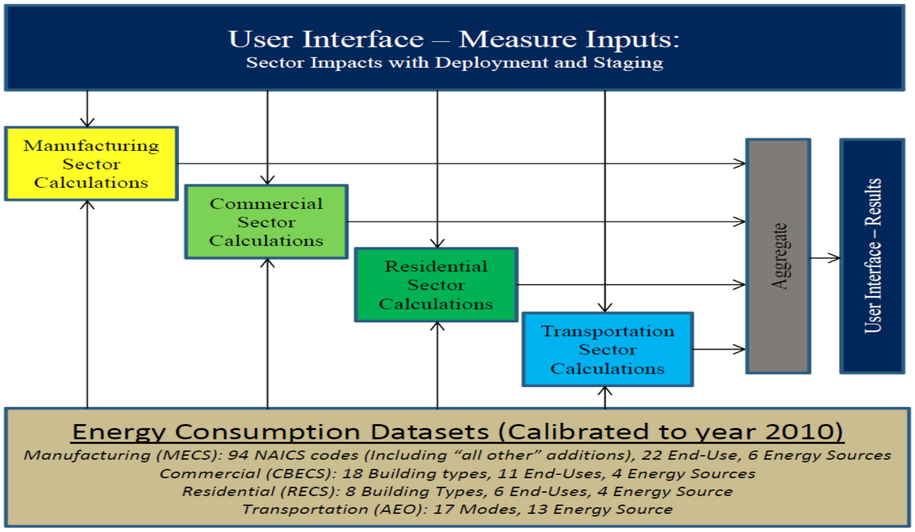
Assessment of energy impacts through the lifecycle can be complex. For example, advances in manufacturing efficiency (lower energy, faster throughput, etc.) and next generation materials can enable greater use phase impacts:

- The intermediate use phase can include industry, and - for our definition - energy production and delivery.
- The end use phase includes, for example, energy demand by vehicles and buildings.

Cross-Sector Modeling Framework Overview

The objective of this analysis is to provide a framework that is both sufficiently intuitive that an energy analyst can use it with minimal training, yet dynamic enough to capture the impacts of measures across the manufacturing, commercial, residential, and transportation sectors of the U.S. economy. Figure 2 presents a graphical representation of the LIGHTEnUP tool.

Figure 2. LIGHTEnUP Tool Cross-Sector Modeling Framework



The LIGHTEnUP tool is contained in a Microsoft Excel spreadsheet and each of the blocks in Figure 2 represents a worksheet tab. The primary user interfaces are the blue shaded blocks in Figure 2, which allow the user to input measure data (sector impacts with deployment and staging) in one location ("User Interface – Measures Inputs") and calculate results in another location ("User Interface – Results"). The LIGHTEnUP tool pulls energy consumption data from datasets ("Energy Consumption Datasets"), simulates the deployment of measures in each of the energy consuming sectors over time ("Manufacturing Sector Calculations", "Commercial Sector Calculations", "Residential Sector Calculations", and "Transportation Sector Calculations"), and aggregates the affects from all sectors together providing summary results.

User Interface: Measure Inputs

Measure inputs consist of sector impacts including deployment and staging. The LIGHTEnUP tool is designed such that measure inputs can be divided into multiple impacts and then aggregated into a single measure heading in results. For example, an advanced carbon fiber technology measure would require manufacturing investments in processes that will alter energy consumption in conceivably multiple manufacturing subsectors as this technology matures and is deployed. Production of carbon fiber would require new capital manufacturing investments as well as impacting the chemical subsector's resin output to manufacture carbon fiber parts. Individual manufacturing subsectors could incorporate carbon fiber parts into their designs requiring additional manufacturing investments (with potentially different energy consumption requirements than incumbent parts). The carbon fiber parts would be utilized by consumers and impact energy consumption in one of the three other major energy consuming sectors (commercial, residential, or transportation). Using this example, three manufacturing subsector impacts could represent a "carbon fiber" measure as well as a single or multiple use-phase impacts. The LIGHTEnUP tool allows each impact to be estimated individually requiring minimal inputs, with the analyst estimating the inter-relationship between sector and subsector impacts. It is designed to allow modeling of straightforward, or complex, dynamics within the same framework.

Deployment and Staging

Measure deployment and staging is modeled using four essential variables: (1) technical potential by end use, (2) relative energy savings, (3) start and (4) end years. An impact reaches its full adoption potential (is fully deployed) by the defined sector and subsector end-use by the end year. The LIGHTEnUP tool applies iterative linear annual adoptions between the start and end years and maintains full adoption beyond the end year[1]. As an example, if a microwave heating technology is expected to be deployed within a manufacturing subsector, knowing how much of the subsector's process heating it would likely replace (e.g., 10% of that subsector's process heating equipment) as well as the relative energy saving between the average incumbent process heating technology and the microwave heating technology (e.g., 50% reduction in process heating energy consumption) defines the full adoption potential (e.g., 10% x 50% = 5% reduction in energy at full adoption). The full adoption potential is applied against business as usual energy consumption to calculate energy savings per measure. An analyst can assume that the technology is adopted over-night (e.g., in 2010) which would only effect the 2010 stock's technical potential, or applied over a period of time (e.g., between 2010 and 2030) which would ramp impacts from zero in 2010 to the full adoption potential by 2030 and maintain full adoption rate potential from 2030 to 2050. Impacts are simple to model but require thoughtful input from the analyst and comparing two alternative investment options requires that both be modeled in similar detail (i.e., either as both "over-night" or as both "deployed" providing cumulative multi-year energy savings).

Impacts can be staged over time using these same four variables. For the example of carbon fiber, carbon fiber production must precede the manufacture of carbon fiber parts, which must precede the use-phase impacts of carbon fiber parts in the market place.

Energy Consumption Datasets

Underlying energy consumption datasets provide a starting point for impact analysis by detailing where energy is currently consumed in manufacturing, building, and transportation sectors of the economy. U.S. DOE EIA Surveys of the U.S. manufacturing sector (EIA 2006) and of the buildings sectors (EIA 2003, EIA 2009 are utilized, while the transportation sector dataset utilizes U.S. DOE EIA Annual Energy Outlook 2013 data (AEO2013) (EIA 2013). The manufacturing and building datasets are calibrated to 2010 based on U.S. DOE EIA historic energy consumption data. Year 2010 is far enough back to provide a reasonably accurate energy consumption benchmark yet close enough to the present for forward energy consumption projections that reflect current infrastructure stocks. Business as usual (BAU) energy consumption forecasts between 2010 and 2050 are calculated as needed for each sector and subsector based on EIA AEO2013 Reference Case economic growth indicators[2] extended to 2050. The economic growth indicators exclude assumptions imbedded in the AEO Reference Case energy consumption forecasts to avoid double counting.

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[1] The time horizon is currently capped at 2050 but can easily be expanded beyond with minor adjustments. 2050 was chosen because of its significance in common greenhouse gas emissions reduction targets. If an impact is anticipated to be fully deployed after 2050, its linearly extrapolated results will only be summed through 2050.

[2] e.g., macroeconomic forecasts for key manufacturing sectors, floor space for commercial buildings, households for residential buildings, and distance traveled for transportation

User Interface: Results

Results are presented per measure for the 2010-2050 time horizons. Y-axes options are energy use or savings (TBtus of final energy, TWhs of end-use electricity, or TBtus of primary energy which includes fuel consumption for grid based electricity generation[3]). Modeled annual energy use and savings are summed from all sectors for all sub-measures along the X-axes of the graph. Results can be shown with, or without, a backdrop of BAU energy consumption.

Case Studies

An initial set of efficiency measures with varying levels of cross-sectorial complexity have been applied in the LIGHTEnUP tool to highlight insights that can be gained from this analysis. Excluded from the analysis presented in this paper are energy consumption from pre-manufacturing upstream processes and end of life recycling impacts. Table 1 presents several representative case studies evaluated in the LIGHTEnUP tool although respect for page limitations for this conference paper requires that only two of the case studies be presented in more detail. Additional case studies will be presented in the conference presentation.

Table 1. Example of Efficiency Measure Case Studies and Applicable Sectors and Stages to Assess

Case Studies	Direct (Manufacturing)	Freight (Transportation)	Use-Phase (Non-Manufacturing)
Combustion Air Preheating	Yes	NA	NA
Novel spinel-based refractory materials	Yes	NA	NA
Light-weighting Packaging Material	Yes	Yes	NA
Fiber Reinforced Polymer (FRP) concrete reinforcing rods	Yes	Yes	NA
Light-Weight Airplanes with aluminum AM Parts	Yes	Yes	Yes
LED lighting in Buildings	Yes	Yes	Yes

Detailed Case Study # 1 – Example: Producing Aluminum Monitor Arms Used to Support Personalized Monitors on Airplanes Using Additive Manufacturing Process

A very limited amount of research has been conducted in the lifecycle energy efficiencies of products made using additive manufacturing (AM) processes to date. When considering the benefits and energy efficiency of AM, it is vital to consider the manufacture, distribution and logistics, and the part use phase. Although AM processes use significantly more energy than conventional processes per unit mass of material processed, they do enable the production of

[3] EIA AEO2013 Reference Case annual U.S. average grid electricity heat rates are used to convert electricity to primary energy.

parts with optimized shapes and geometric features that reduce raw materials and component weight. For aircraft parts, the primary environmental and energy efficiency benefit of AM is during the use phase of the part. By enabling optimized part manufacture, significant weight savings can be realized, which can greatly reduce the fuel consumption of aircrafts.

The Atkins project was set out (May 2008 – April 2012) to understand and quantify the energy efficiency and environmental benefits of using the AM process for the production of components within the aerospace and automotive supply chain (Atkins 2011). Aircraft TV monitor arms were redesigned using topological optimization software to significantly reduce mass while maintaining strength and stiffness. The parts were then manufactured using laser sintering or selective laser melting (SLM). AM processes were found to consume between 10 and 100 times more energy per kg of material processed than computer numerical control (CNC) machines but reducing the weight by 2.38kg/arm for these parts. Despite increasing the direct energy required to manufacture the part, the AM process reduces embodied manufacturing sector energy through the reduction of aluminum requirements. However, these savings are relatively minor compared to the use-phase energy savings that lighter aircraft parts allow if deployed into airline fleets.

Table 2 presents the measure inputs to the LIGHTEnUP tool to reflect the deployment of AM TV monitor arms into U.S. airline fleets. A separate worksheet documents assumptions regarding airplane and manufacturing energy calculations necessary for the inputs presented in Table 2[4]. This measure deployment and staging assumes that all phases are staged simultaneously.

Table 2. LIGHTEnUP Tool Aircraft TV Monitor Arm Measure Impact Inputs

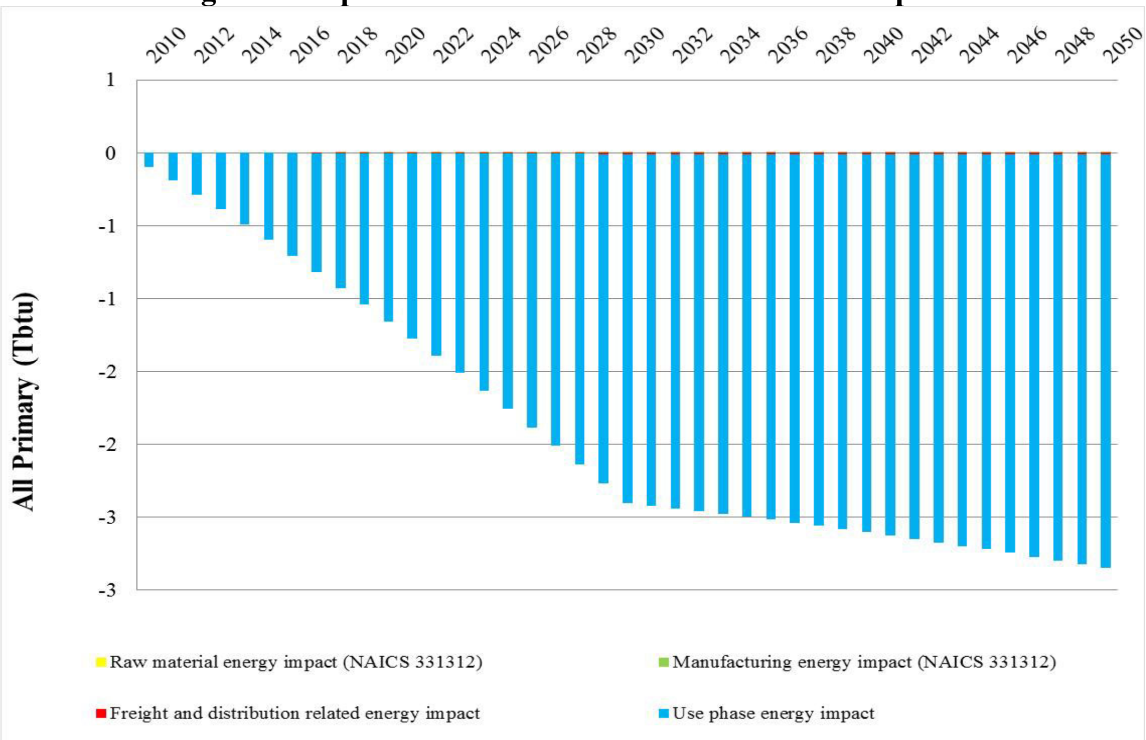
Sector	End-Use	Technical Adoption Potential %	Relative Energy Savings %	Start Year	End Year
Manufacturing (Raw material energy savings, Primary Aluminum (NAICS 331312))	All Fuels – Total Fuel Consumption	100%	0.006%	2010	2030
Manufacturing (SLM Vs CNC machining, Primary Aluminum (NAICS 331312))	All Fuels – Total Fuel Consumption	100%	(-) 0.000005%	2010	2030
Transportation (for part – Freight Trucks)	Diesel	100%	0.001%	2010	2030
Use Phase (Airplane Transportation – Air Transportation)	Jet Fuel	100%	0.08%	2010	2030

Figure 3 shows the energy savings potential within the measure's sector and subsector end-use categories over the 2010-2050 time horizons. Manufacturing energy consumption is basically balanced between an increase in energy consumption to manufacture the arms and a decreased energy consumption to produce the raw aluminum, the resulting manufacturing energy impact is small in Figure 3. The manufacturing and the transport of the parts are almost entirely

[4] This documentation can be provided upon request

obscured in Figure 3 due to the relatively large savings from the use phase. Most of the benefits are attributed to the use-phase reduction in jet fuel consumption and results are shown without a BAU energy consumption benchmark[5].

Figure 3. Replace all 747 TV monitor arms with AM parts



Detailed Case Study # 2 – Light Emitting Diode (LED) Lighting in Buildings

LED lighting holds great potential to reduce the energy demand in building operations. However, differences in upstream and downstream energy impacts of LED lighting relative to more conventional technologies (e.g., incandescent, florescent) require a system-wide analysis. The LIGHTEnUP tool is used to estimate the energy implications of shifting U.S. light bulb manufacturing from conventional technologies to LED lights, at a rate that supplies all U.S. building lighting demand in 20 years. The impacted sectors and assumed saving percentage inputs applied to the tool are presented in Table 3

Building operational energy savings from improved lighting efficiency of LED is applied to all residential, commercial, and manufacturing building stock. Similar to the previous case study, a detailed documentation of calculations and assumptions provide the inputs presented in[6].

[5] The choice to not show a BAU energy consumption benchmark reflects that fact that the energy savings potentials are dwarfed by the magnitude of energy consumption; however, this should not hide the fact that anticipated energy benefits exists.

[6] This documentation can be provided upon request

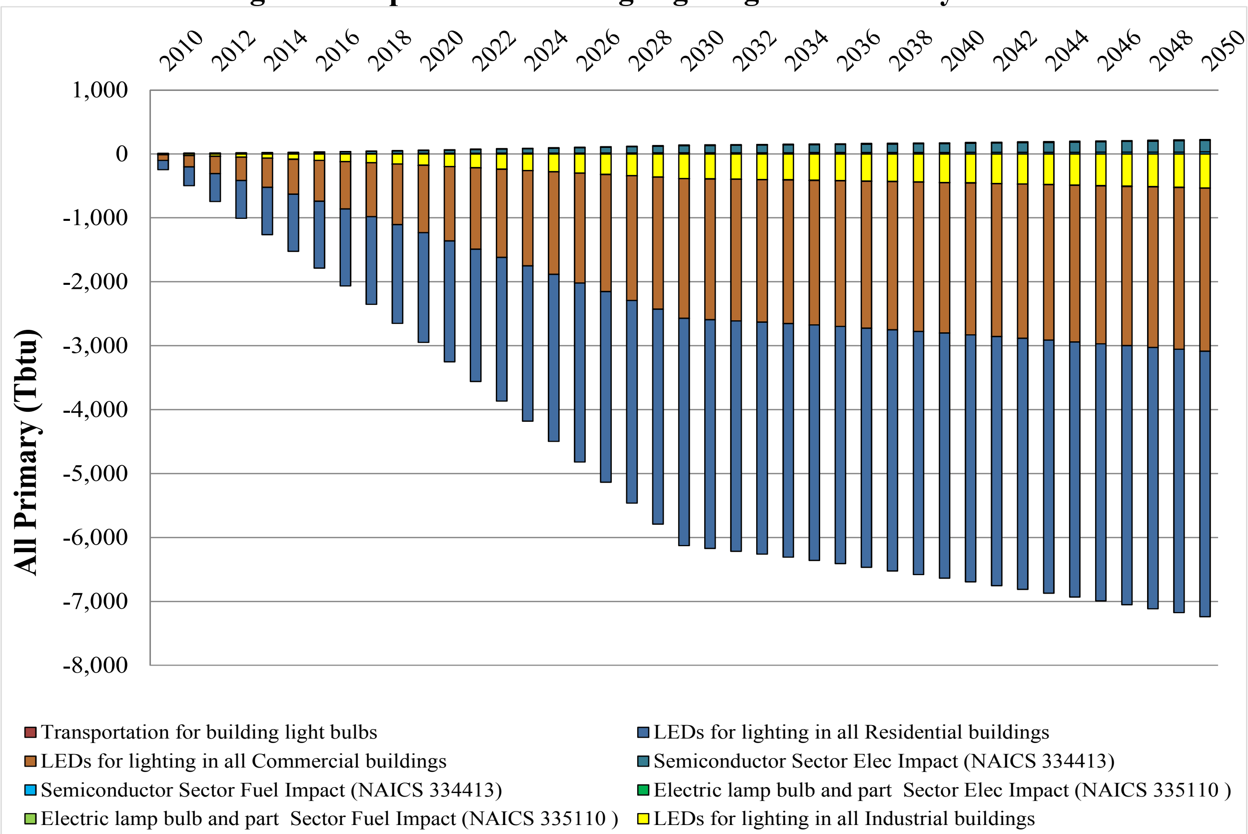
Table 3. LIGHTEnUP Tool LED Measure Impact Inputs

Sector	End-Use	Technical Adoption Potential %	Relative Energy Savings %	Start Year	End Year
Manufacturing (Electrical equipment, appliance, and component manufacturing (NAICS 335))	All Fuels – Total Fuel Consumption	100%	1.2%	2010	2030
Manufacturing (Electrical equipment, appliance, and component manufacturing (NAICS 335))	Electricity – Total Fuel Consumption	100%	1.2%	2010	2030
Manufacturing (Semiconductor Sector Fuel Impact (NAICS 334413))	All Fuels – Total Fuel Consumption	100%	-66.2%	2010	2030
Manufacturing (Semiconductor Sector Fuel Impact (NAICS 334413))	Electricity – Total Fuel Consumption	100%	-66.2%	2010	2030
Transportation (for light bulbs – Freight Trucks)	Diesel	100%	-0.15%	2010	2030
Use Phase (LEDs for lighting in all Residential buildings)	Electricity – Other	70%	60%	2010	2030
Use Phase (LEDs for lighting in all Commercial buildings)	Electricity – Lighting	98%	48%	2010	2030
Use Phase (LEDs for lighting in all Manufacturing buildings)	Electricity – Facility Lighting	100%	44%	2010	2030

The negative energy savings in the semiconductor sector (NAICS 334413) represents the increased annual energy use to manufacture enough LED lighting to meet all building illumination demand by 2030. This annual manufacturing energy increase of approximately 100 TBtu is estimated by accounting for total building floor space in 2030 (EIA 2013), 2010 illumination requirements (lm/ft^2) (EERE 2012a), and the illumination and manufacturing energy associated with near-future LED lighting (EERE 2012b). Since the operating lifetime of near-future LED lights is approximately 40,000 hours (EERE 2012b), turnover is assumed to be minimal during this 20-year period. The negative energy savings in the transportation sector represents the increased annual energy use to ship enough LED lighting to meet all building illumination demand by 2030, relative to current lighting shipments. Energy associated with current shipments of lights for buildings is estimated by scaling U.S. census data for values of shipments for dedicated building lamp bulbs and parts (USDOC 2007) to the total value of commercial freight shipments (USDOT 2004). The increase in transportation energy is then estimated by accounting for the increase in number and weight of LED lights relative to the current annual domestic production of building lights (assumed to be incandescent).

Figure 4 presents the changes in energy use for the different impacted sectors, with the building operational energy representing annual savings at full penetration in 2030, and the manufacturing and transportation energy representing the annual energy use required to meet this LED penetration by 2030.

Figure 4. Replace All Building Lighting with LEDs by 2030



As presented in Table 3, the manufacturing energy consumption increases in the semiconductor sector while decreasing in the electrical equipment, appliance, and component sector for manufacturing to transition from incandescent light bulbs to LED light bulbs. However, the realized energy savings benefit from LED lighting is in the use phase. Significant savings can occur in both the residential and commercial sectors as well as industrial buildings.

Conclusions

The LIGHTEnUP analysis tool aims to capture both the manufacturing sector energy consumption and product use-phase energy consumption implications of manufacturing energy related measures. This broader scope of analysis can provide a more thorough understanding of measure benefits, but creates increased complexity when mapping impacts across different manufacturing and non-manufacturing sectors of the economy. In developing this analysis tool, to provide a manufacturing and use-phase analysis, several main challenges emerge.

First, the approach of developing an intuitive framework that is straightforward to utilize shifts the burden of calculation documentation from this tool to external sources. The LIGHTEnUP tool only requires four simple inputs per impact assessment (per sector and end-use). However deriving those inputs is not simple and transparency necessitates additional documentation methodologies which have been developed in parallel with this tool to provide a repository of driving assumptions, calculations, and references. This should allow for refinement of analysis results as the future changes and new information emerges while maintaining a "simple" framework for impact analysis.

Second, supply chain energy impacts and implications of measures analyzed by this tool are not implicitly imbedded in the architecture. Additionally, the tool's treatment of the electricity sector as well as the interconnected nature of the manufacturing sector as a whole are not treated explicitly within the tool; however, we do plan to evolve the tool architecture include those factors. Modeling large-scale derivations from current practices increases the uncertainty of the results as they could have rippling effects through other sectors and subsectors that must be carefully understood and modeled accordingly.

Lastly, although costs are another important variable in the analysis and decisions making processes, this paper is focused on the energy flow and impact modeling rather than cost-effectiveness evaluations. The tool does have the ability to model costs associated with measures but this aspect is still in the development phase. The tool is also being designed to evaluate larger economy-wide metrics such as value added to U.S. gross domestic product and innovation leadership value for the U.S economy in a global context.

While still in nascent form, the LIGHTEnUP tool currently provides a larger economy-wide prospective of the potential benefits available from the implementation of different manufacturing efficiencies and innovation measures. As the model matures, such results can guide advanced manufacturing investments toward products that lower consumer's energy consumption and environmental foot prints and bolstering U.S. manufacturing capacity, thus leading to more energy and environmentally sustainable future.

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